0.a. Goal

Goal 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

0.b. Target

Target 14.3: Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels

0.c. Indicator

Indicator 14.3.1: Average marine acidity (pH) measured at agreed suite of representative sampling stations

0.e. Metadata update

15 February 2021

0.f. Related indicators

14.a.1 Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries

0.g. International organisations(s) responsible for global monitoring

Intergovernmental Oceanographic Commission (IOC) of UNESCO

1.a. Organisation

Intergovernmental Oceanographic Commission (IOC) of UNESCO

2.a. Definition and concepts

Definitions:

Ocean acidification is the reduction in the pH of the ocean over an extended period, typically of decades or longer, which is caused primarily by the uptake of carbon dioxide from the atmosphere[1].

This indicator is based on observations that constrain the ocean carbon system and which are required to describe the variability in ocean acidity. The carbon system in this context mainly refers to the four measurable parameters: pH (the concentration of hydrogen ions on a logarithmic scale), DIC (CT; total dissolved inorganic carbon), pCO_2 (carbon dioxide partial pressure), and TA (AT, total alkalinity). Average, as used here, is the equally weighed annual mean.

An agreed suite of representative sampling stations are sites that have a measurement frequency that is adequate for describing variability and trends in carbonate chemistry in order to deliver critical information on the exposure of and impacts on marine systems to ocean acidification, and which provide data of sufficient quality and with comprehensive metadata information to enable integration with data from other sites in the country.

Concepts:

Ocean acidification is caused by an increase in the amount of dissolved atmospheric CO_2 in the seawater. The average marine acidity is expressed as pH, the concentration of hydrogen ions on a logarithmic scale. In order to be able to constrain the carbonate chemistry of seawater, it is necessary to measure at least two of the four parameters, i.e. pH, pCO_2, DIC (CT), and TA (AT). pH (the concentration of hydrogen ions on a logarithmic scale, expressed on total scale), DIC (total dissolved inorganic carbon, in µmol kg^{-1}), pCO_2 (carbon dioxide partial pressure, in ppt or µatm), and TA (AT, total alkalinity, in µmol kg^{-1}).

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[1] NOAA. What is ocean acidification? National Ocean Service website https://oceanservice.noaa.gov/facts/acidification.html, 06/25/18 ↑

2.b. Unit of measure

pH on total scale

and/or pCO_2 [µatm or ppt], DIC [µmol kg^{-1}], TA [µmol kg^{-1}]

2.c. Classifications

The SDG indicator 14.3.1 methodology was endorsed by IOC Member States at the Fifty-first Session of the IOC Executive Council (IOC/EC-LI/2 Annex 6 rev). The methodology was further community approved as an Ocean Best Practice (http://dx.doi.org/10.25607/OBP-655).

3.a. Data sources

The general IOC data collection process is described in Document IOC-XXIX/2Annex 14.

The novelty of assessing ocean acidification at the global level, as in indicator 14.3.1, requires the IOC secretariat to collect the data via different pathways. Data collections are a mixture of:

- direct requests to National Statistical Offices (NSOs), as new national reporting mechanisms are now installed allowing them to provide the required information (from the 2021 data collection

onwards),
- annual requests to the IOC national focal points,
- collaboration with National Oceanographic Data Centres, international data centres and
- directly with data providers via the GOA-ON data portal (Figure 1).

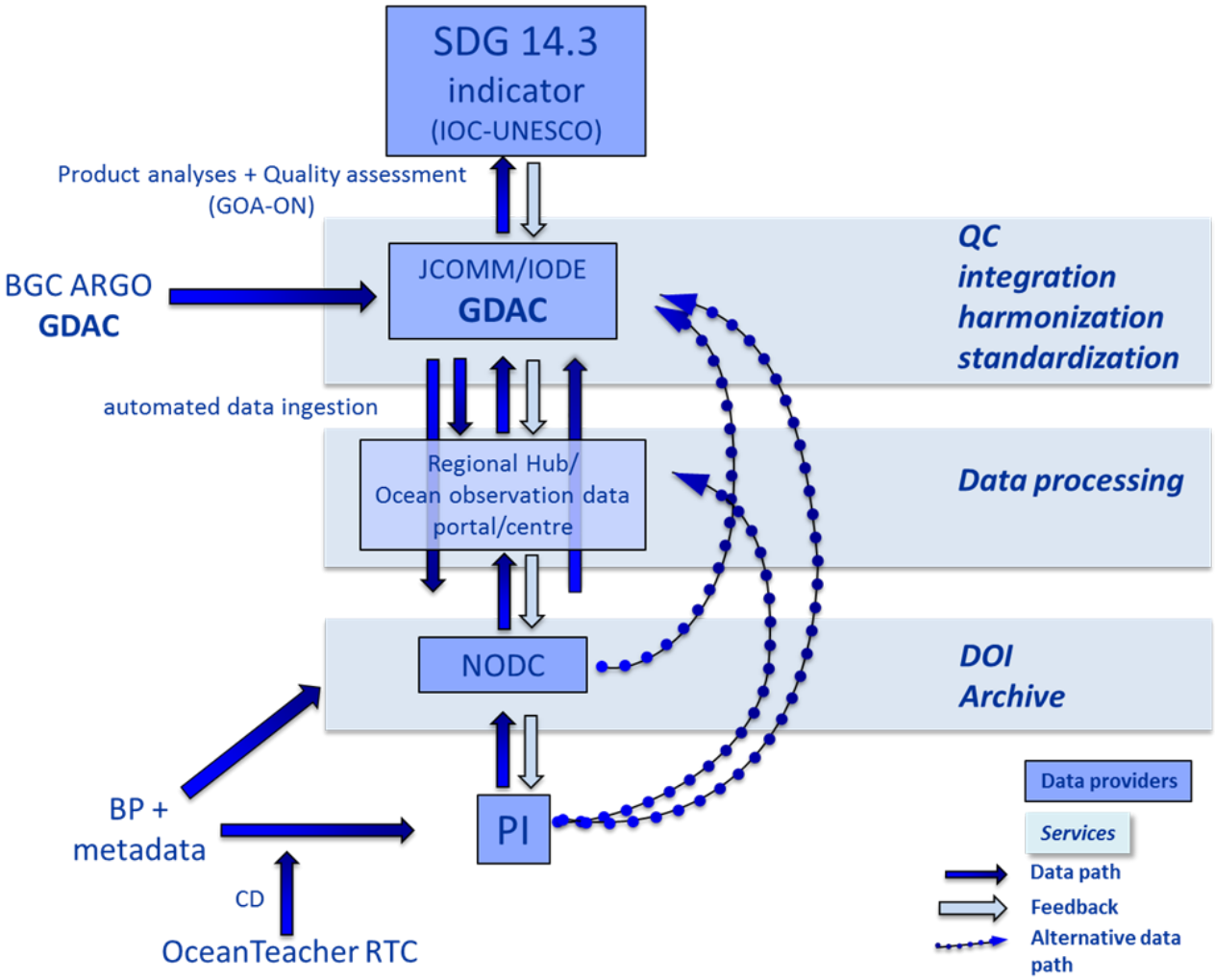

Figure 1. Scheme to illustrate the proposed data collection and publication process related to national contributions of data related to 14.3.1 (SDG: Sustainable Development Goal; IOC-UNESCO: Intergovernmental Oceanographic Commission of UNESCO; GOA-ON: Global Ocean Acidification – Observing Network; JCOMM: WMO-IOC Joint Technical Commission for Oceanography and Marine Meteorology; WMO: World Meteorological Association; IODE: International Oceanographic Data and Information Exchange of IOC UNESCO; GDAC: Global Data Assembly Center; BGC ARGO: Biogeochemical Argo floats; QC: Quality Control; NODC: National Oceanographic Data Centre; DOI: Digital Object Identifier; BP: Best Practice; CD: Capacity Development; PI: Principal Investigator; RTC: Regional Training Centre).

Global scientific efforts (GO-SHIP, SOCAT, GCOS) which host and feature data from various ocean observing efforts and/or focus on collecting measurements in international waters will also be queried for annual or more likely multi-year data sets representing status and change of ocean acidification variables in the open ocean.

The data collection process takes place in close collaboration with the IOC Project Office for IODE Oostende, Belgium and relevant data providers/national archives, the GOA-ON data portal, and entities such as the marine chemistry part of the European Marine Observation and Data Network (EMODnet). Since 2019 IOC invites all data providers to use the newly established SDG 14.3.1 Data Portal (http://oa.iode.org). This SDG 14.3.1 Data Portal is a tool for the submission, collection, validation, storage and sharing of ocean acidification data and metadata submitted towards the

Sustainable Development Goal 14.3.1 Indicator: Average marine acidity (pH) measured at agreed suite of representative sampling stations. Besides allowing for a direct submission of metadata and data, the portal further provides the full text of the SDG 14.3.1 Indicator Methodology, the data template, the metadata template and the metadata instructions file. Since 2020 a newly developed FAQ section facilitates the provision of 14.3.1 data.

Furthermore the GOA-ON data portal features open access data, in addition to a global monitoring asset inventory. The portal is designed to offer two levels of access: 1) visualization and 2) download capabilities. Combining different open-access data sets may provide incentives to create new observing systems in under-sampled areas and to increase the application of open access data policies worldwide, according to the IOC Criteria and Guidelines for the Transfer of Marine Technology (2005) in the future.

Furthermore, the GOA-ON website hosts a number of pages dedicated to the SDG 14.3.1 methodology: http://goa-on.org/sdg_14.3.1/sdg_14.3.1.php.

3.b. Data collection method

The official counterparts are the IOC focal points. They, as well as National Oceanographic Data Centres (NODCs), are contacted by IOC to request relevant data from the appropriate national oceanographic data centres and/or relevant scientists, agencies or programmes. An annual data submission request is sent out via IOC Circular Letters directly to the member states asking for the respective data and metadata (through circular letter 2792 in 2019 and circular letter 2815 in 2020). New updates and the inclusion of new features to the SDG 14.3.1 data portal to be developed in 2021 will facilitate with collaboration with other existing ocean carbon data centres and biogeochemical data platforms.

Furthermore, IOC benefits from direct contributions from ocean acidification scientists organized within the Global Ocean Acidification Observing Network (GOA-ON) to the SDG 14.3.1 data portal.

All contributors of data to SDG 14.3.1 are encouraged to read and follow the standard operating procedures provided in Dickson et al. 2007. This document covers ocean carbon chemistry, sample-handling techniques, quality assurance procedures, the use of Certified Reference Materials (CRMs) and Standard Operating Procedures (SOPs) for discrete sampling of pH, pCO_2, TA, and DIC. Data contributors are also encouraged to read the Guide to Best Practices in Ocean Acidification Research and Data Reporting, which focuses on best practices for laboratory experiments, but also includes background on carbon chemistry (Riebesell et al. 2010). For coastal environments, which can be subject to large variability and a range of influences, such as nutrient and freshwater inputs, guidelines for the measurement of pH and carbonate chemistry can be found here (Pimenta and Grear 2018)

All data submitted to SDG 14.3.1 must include an estimate of measurement uncertainty in the metadata. Autonomous sensors for pH and pCO_2 require calibration and maintenance to validate sensor performance and identify drift or sensor malfunction. Where possible, the analysis of discrete bottle samples analysed for pH, DIC or TA collected next to the sensors can be used to calculate pH and pCO_2.

All ocean acidity datasets submitted to SDG 14.3.1 must also include associated temperature (in situ [and temperature of measurement if different than in situ]), salinity, and pressure (sampling depth). If submitting pH values, all pH values must be on the total scale (Dickson et al. 2007).

3.c. Data collection calendar

National data sets should be reported annually (at the least), following the request by IOC Circular letters. However, experts, national focal points of Member States and NODCs are invited to submit data throughout the year via the SDG 14.3.1 data portal. The next invitation via a Circular Letter will be send in during the second semester of 2021.

3.d. Data release calendar

Data are released in February each year.

3.e. Data providers

The general IOC data collection process is described in Document IOC-XXIX/2Annex 14.

The novelty of assessing ocean acidification at the global level, as for this indicator 14.3.1, requires the IOC secretariat to collect the data via a range of different pathways. This will include direct requests to National Statistical Offices (NSOs), annual requests to the IOC national focal points, and NODCs and associated data agencies in the member states, as well as international data centres and individual data providers.

3.f. Data compilers

The Intergovernmental Oceanographic Commission (IOC) of UNESCO is the custodian agency for this Indicator. In collaboration with the International Oceanographic Data and Information Exchange (IODE) of IOC, the data will be collected and stored in a transparent and traceable manner, allowing for the ocean acidification data to be shared. IOC welcomes data sets which can be freely shared without restrictions (CC0, CC BY), with restrictions for commercial use (CC BY-NC), as well as those which only allow for IOC-UNESCO to derive products used for the purpose of the SDG indicator 14.3.1 reporting (http://oa.iode.org).

3.g. Institutional mandate

IOC-UNESCO is the custodian agency for the SDG indicator 14.3.1. The purpose of the Commission is to promote international cooperation and to coordinate programmes in research, services and capacity-building, in order to learn more about the nature and resources of the ocean and coastal areas and to apply that knowledge for the improvement of management, sustainable development, the protection of the marine environment, and the decision-making processes of its Member States. In addition, IOC is recognized through the United Nations Convention on the Law of the Sea (UNCLOS) as a competent international organization in the fields of Marine Scientific Research (Part XIII) and Transfer of Marine Technology (Part XIV). According to its Statutes, the Commission may act also as a joint specialized mechanism of the organizations of the United Nations system that have agreed to use the Commission for discharging certain of their responsibilities in the fields of marine sciences and ocean services, and have agreed accordingly to sustain the work of the Commission. IOC is further one of the organizations supporting the Global Ocean Acidification Observing Network (GOA-ON) (http://goa-on.org). The Commission hosts one part of the distributed GOA-ON Secretariat, fostering science collaboration and capacity building in ocean acidification observations. GOA-ON actively encourages its members to collect and report metadata and data relevant for the SDG indicator 14.3.1.

4.a. Rationale

The ocean absorbs up to 30% of the annual emissions of anthropogenic CO_2 to the atmosphere, helping to alleviate the impacts of climate change on the planet. However, this comes at a steep ecological cost, as the absorbed CO_2 reacts with seawater and results in shifts in the dissolved carbonate chemistry including increased acidity levels in the marine environment (decreased seawater pH). The observed changes have been shown to cause a range of responses at the organism level that can affect biodiversity, ecosystem structure and food security. For example, a decrease in dissolved carbonate reduces the solubility of carbonate minerals including aragonite and calcite, the two main forms of calcium carbonate used by marine species to form shells and skeletal material (e.g. reef building corals and shelled molluscs). Aragonite is the more soluble form and its availability for shell building by organisms such as corals and oysters, called the aragonite saturation state [Ω (aragonite)], is used together with pH as an indicator in tracking the progression of ocean acidification. In addition, of equal importance to some key marine organisms, is the dissolved CO_2 and bicarbonate concentration. It is, therefore, of the upmost urgency that a full categorization of the changing carbonate system is delivered.

Regular observations of marine acidity at open-ocean locations over the past 20-30 years have revealed a clear trend of decreasing pH and that present-day conditions are often outside preindustrial bounds. Observational trends in coastal areas have been reported to be more difficult to determine. In some regions, the changes are amplified by natural processes like upwelling (whereby cold, often CO_2 and nutrient rich, water from the deep rises toward the sea surface). In addition, other factors, including freshwater run-off, ice-melting, nutrients, biological activity, temperature change and large ocean oscillations influencing carbon dioxide levels, particularly in coastal waters, need to be taken into account when interpreting drivers of ocean acidification and the related impacts. Ocean acidification has potentially direct consequences for marine life and cascades through to the services provided by the open ocean and coastal areas including food and livelihood, tourism, coastal protection, cultural identity, transportation and recreation. The impacts on ocean services from ocean acidification may be lessened through appropriate monitoring and improved understanding of variability and rates of change, helping to inform mitigation and/or adaptation strategies.

Although this indicator requests “average acidity” values from nations, the data which comprises the average ought to provide insight into the variability of the measurements, which is more relevant for the impact on marine life. In other words, species do not respond to “average” conditions, but to real time conditions. At a minimum, the total range (minimum and maximum values) should be reported in addition to the average.

Coastal countries often have long-term monitoring of water quality, including information on nutrient concentrations, temperature, salinity and occasionally carbonate chemistry. These water quality monitoring sites provide historical context about biogeochemical variability of the system and should be considered ideal location for ocean acidification monitoring. Additional sites may also need to be established to characterize variability.

The data variables associated with the monitoring of ocean acidification (variables include pH, carbon dioxide partial pressure [pCO_2], total dissolved inorganic carbon [DIC], and total alkalinity [TA]) have the potential to serve global, national, regional, and local data needs, such as tracking the exposure of marine ecosystems and aquaculture sites to corrosive conditions, and identifying opportunities to reduce ecosystem and economic vulnerability to ocean acidification. For example, local monitoring of pH and aragonite saturation state on the Pacific coast of the United States has enabled shellfish farmers to adapt to damaging conditions present during upwelling events, which reduce pH and threaten brood stock.

4.b. Comment and limitations

The methodology for this indicator has been developed with the technical support of experts in the field of ocean acidification. It provides globally accepted and adapted guidelines and best practices established by scientists and published in peer-reviewed literature.

As this is a highly complex indicator, the technical infrastructure necessary for the correct measurement is a potentially constraining factor. The Methodology for the indicator describes how to avoid comparability issues of the data, which have been problematic in the past, as well as measurement errors and advises on the most appropriate technical and methodological procedures to guarantee high-quality data that can be used for the global assessment of ocean acidification. The addition of metadata to the methodology for this indicator is crucial for adding traceability and transparency to the data, by providing information on the precise equipment and methodology used, as well as specifying the location, accompanying biogeochemical variables and the person taking the measurement.

4.c. Method of computation

Detailed information in Attachment I IOC/EC-LI/2 Annex 6.

This indicator calls for the collection of multiple observations, in the form of individual data points, to capture the variability in ocean acidity. Individual data points for pH either are measured directly or can be calculated based on data for two of the other carbonate chemistry parameters, these being TA (AT), DIC (CT) and pCO_2. Calculation tools developed by experts in the field are freely available, and they are introduced and linked in the methodology. Average pH is defined as the annual equally weighed mean of multiple data points at representative sampling stations. The exact number of samples and data points depends on the level of variability of ocean acidity at the site in question. The minimum number of samples should enable the characterisation of a seasonal cycle at the site. Detailed guidelines on the minimum number of observations required are provided in the Methodology (https://oa.iode.org). In addition to the data value, standard deviation and the total range (minimum and maximum values measured), as well as underlying data used to provide traceability and transparency (metadata information) should be reported. All reported values should have gone through a first level quality control by the data provider. If historical data is available, this should be released to enable calculations about the rate of change and to compare natural variability and anthropogenic effects.

Relevant data from 2010 onwards are accepted.

4.d. Validation

The counterparts are invited to provide references (metadata) for the information provided. Data provided by experts, who are not representatives of NODCs or IOC Member States, are sent for national validation to the relevant official counterparts.

Further IOC receives verified information by the identified representatives of its Member States directly, which entails the validation necessary to be published for the SDG indicator 14.3.1 assessments

4.e. Adjustments

The 14.3.1 data and metadata files give detailed information about the requested data and metadata to report. Data and metadata files contain compulsory variables to be reported and additional variables to be included if available.

Data providers/Member States are encouraged to submit primary quality controlled data sets of two variables characterizing the carbonate system: pH, TA, DIC or pCO_2, plus precise location, temperature, salinity and hydrostatic pressure (sampling depth) (see Quality control). Depending on data quality, different categories will be assigned to the submitted data sets. In addition, corresponding macro nutrient concentrations are requested, if nitrate, phosphate and silicate data are available (see Data quality). Further, data providers will be invited to submit all data, independent of where the data were collected within the water column; however, they are encouraged to provide surface data (≤ 10 m).

4.f. Treatment of missing values (i) at country level and (ii) at regional level

At country level

Some missing values may be modelled or calculated if established methodologies exist (see Recommendations for calculation of the carbonate system in IOC/EC-LI/2 Annex 6).

At regional and global levels

Regional aggregates are permissible if more than 50% of coastal nations have reported values.

4.g. Regional aggregations

Every country or nominated IODE National Oceanographic Data Centre (NODC)/Associated Data Unit (ADU)[2] will provide annually updated data sets. Aggregations across regions will require data of comparable quality and all relevant metadata with site-specific information be included in the data sets. Due to the variability of measurements and the prevalence of areas with high variability in ocean acidity, the aggregation of measurement averages (equally weighed annual mean) across coastal marine habitat and ecosystem types is difficult to interpret and is therefore discouraged.

2 https://www.iode.org/index.php?option=com_oe&task=viewGroupRecord&groupID=349 ↑

4.h. Methods and guidance available to countries for the compilation of the data at the national level

The SDG 14.3.1 Indicator Methodology presented in the document IOC-XXIX/2Annex 14, IOC/EC-LI/2 Annex 6 provides guidelines for the collection of measurements towards the Indicator. Data and metadata files in which all of the relevant measurements should be compiled will be provided to the data centre or data originator. This data will be collected by the relevant national data centers, such as National Statistical Offices (NSOs) and National Oceanographic Data Centers (NODCs), and shared with the Indicator's custodian agency, the IOC of UNESCO[3].

The Indicator Methodology comprises an overview of statements on best practice and links to several Standard Operating Procedures (SOPs). These procedures represent the best practices compiled by the leading researcher in the field and have been made freely available. A list of relevant material, as referenced in the Indicator Methodology, can be found here: http://www.ioccp.org/index.php/documents/standards-and-methods

Table 1. List of standard operating procedures to measure different parameters of the carbonate system (procedures marked with * are able to attain climate quality).

	Discrete	**Underway**	**Fixed autonomous sensors**
pH	Spectrophotometric * Potentiometric	Spectrophotometric ISFET	Spectrophotometric ISFET
CT	IR detection Coulometry *		
AT	Potentiometric titration (open and closed cell; open recommended) *		
***p*CO$_2$**		Equilibration, headspace * Membrane-based	Equilibration * Membrane-based

The document IOC-XXIX/2Annex 14, IOC/EC-LI/2 Annex 6 further provides guidance on sampling strategies, sampling frequencies, recommendations for calculation of the carbonate system and uncertainty of measurement.

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[3] IOC-XXIX/2Annex 14, IOC/EC-LI/2 Annex 6 ↑

4.i. Quality management

For the purposes of SDG 14.3.1, three categories of measurement quality were established (adapted from Newton et al. 2015):

Category 1: Climate quality

The climate quality objective is typically used to determine trends in the open ocean, shelf and coastal waters, providing data on seasonal through interannual variability on regional scales. The climate quality objective requires that a change in the dissolved carbonate ion concentration to be estimated at a particular site with a relative standard uncertainty of 1%. The carbonate ion concentration is calculated from two of the four carbonate system parameters and implies an uncertainty of approximately 0.003 in pH; of 2 μmol kg^{-1} in measurements of TA and DIC; and a relative uncertainty of about 0.5% in the pCO_2. Such precision is only currently achievable by a limited number of laboratories and is not typically achievable for all parameters by even the best autonomous sensors.

Category 2: Weather quality

The weather quality objective is suitable for many coastal and nearshore environments, particularly those with restricted circulation or where CO_2 system parameters are forced by processes like upwelling, pollution or freshwater inputs that can cause large variability. The weather objective requires the carbonate ion concentration (used to calculate saturation state) to have a relative standard uncertainty of 10%. This implies an uncertainty of approximately 0.02 in pH; of 10 μmol kg^{-1} in measurements of TA and DIC; and a relative uncertainty of about 2.5% in pCO_2. Such precision should be achievable in competent laboratories, and is also achievable with the best autonomous sensors.

Category 3: Measurements of undefined quality

For SDG 14.3.1, pH measurements using glass electrodes will be considered Category 3 due to the challenges of using glass pH electrodes in seawater. It is intended that the methodology provided here gives useful information for countries building capacity towards Category 1 and 2 measurements. For example, carefully calibrated glass pH electrodes may help in the identification of coastal ocean acidification hot spots and help prioritize future monitoring plans. In annual SDG 14.3.1 summary products, Category 3 measurement sites will be presented as data collection sites only, no data values will be visualized.

All those contributing data to SDG 14.3.1 are encouraged to adopt measurement quality Category 1 or 2. A variety of capacity development activities to support Member States' capacity in this regard are conducted by different organizations (more information can be found here: e.g. www.iaea.org/ocean-acidification; http://ioccp.org; http://www.ioc-cd.org/index.php; http://www.whoi.edu/courses/OCB-OA/).

4.j. Quality assurance

Data quality control and validation processes were developed in close consultation with experts in the field of ocean acidification, amongst them members of the Global Ocean Acidification Observing Network (GOA-ON) and data management experts, like the ones at IODE. Data quality control is a critical component of the data analysis, submission and processing. Scientists and technicians who collected the submitted data will be responsible for the primary quality control of the data and accompanying detailed metadata. The metadata submitted with the data must also describe the quality control standard operating procedures (SOPs) followed for each parameter.

Primary quality control by data provider consists of:

- Quality control that is attached to the methodology (CRMs, tris buffer calibration, SOPs are provided),
- Quality control and quality assurance of the actual data (SOPs are provided) and usage of community agreed quality flags,
- Identifying and flagging of outliers,

- Making determinations regarding validity of those outlying points,
- Estimating uncertainty of the measurement,
- Identifying all the sources of uncertainty in the measurements,
- Rolling up the individual uncertainties into overall uncertainty (error propagation).

Secondary quality control by IOC Secretariat and experts:

- Harmonization of the data and ensuring metadata completeness,
- External quality control/audit – Expert QC Group applying the weather and climate levels as defined by GOA-ON (following the example of SOCAT),
- Feedback to data holders.

4.k. Quality assessment

Following the quality control management and assurance mechanisms described in 4.i and 4.j, three categories of measurement quality will be attributed to the individual data sets

1. Established oceanographic climate quality (Category 1)
2. Weather quality data including that from sensors and capacity building simplified pH and alkalinity measurements, with appropriate uncertainty assessment (Category 2)
3. Measurements of undefined quality (Category 3) (will not be displayed in the visualization of annual weighted means and variance of pH).

5. Data availability and disaggregation

Data availability:

Metadata and data availability continuously increase. In early 2021, SDG 14.3.1 data from different national and national data bases were provided directly via the SDG 14.3.1 data portal (http://oa.iode.org).

In order to close existing data gaps to a) measure ocean acidification and b) to report SDG indicator 14.3.1 metadata and data, IOC, together with partners, conducts trainings and webinars. A new ocean acidification online course will be available during the first semester of 2021 (https://classroom.oceanteacher.org/tag/index.php?tc=1&tag=Ocean%20acidification). Past and future trainings are announced on the Ocean Expert (https://oceanexpert.org/events/calendar) and GOA-ON website (http://goa-on.org/news/news.php).

Disaggregation:

Countries provide complete data sets with respective site-specific data and metadata files.

6. Comparability/deviation from international standards

As this indicator only considers data submitted by Member States, there are no discrepancies between estimates and submitted data sets. In the past, differences between countries in the measurement of pH and other ocean acidification data were mainly attributable to technical difficulties and the lack of comprehensive guidelines for the best practice of measurements. The present Methodology and the guidelines contained within provide detailed instructions on the measurement, collection, treatment and quality control of data in a way that will enable countries to avoid future discrepancies.

7. References and Documentation

Main URLs:

IOC-UNESCO http://www.ioc-unesco.org/

IODE https://www.iode.org/; https://oa.iode.org

GOA-ON http://goa-on.org/

GOA-ON data portal http://portal.goa-on.org/

Document IOC/EC-LI/2 Annex 6 -14.3.1 Methodology http://ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=21938

Document IOC-XXIX/2Annex 14 http://www.ioc-unesco.org/index.php?option=com_oe&task=viewDocumentRecord&docID=19589

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